THE SIGNIFICANCE OF LAMINAR CORROSION DEFECTS IN AIRCRAFT

Graham Clark, Khan Sharp
DSTO Aeronautical and Maritime Research Laboratory, Melbourne, Australia

Keywords: *Fatigue, Corrosion, Stress-Corrosion, Structural Integrity*

Abstract

Laminar corrosion defects, such as intergranular penetrations and stress corrosion cracks, are common in ageing aircraft. These defects are most commonly found in extruded and rolled sections made from high strength aluminium alloys; typical examples include wing and tailplane spar caps in widespread use in ageing aircraft. They present a significant problem in that the assessment of their significance is difficult, not only because their orientation (most commonly parallel to the direction of applied stress) makes analysis difficult using conventional stress analysis techniques, but because of the inherent variability of the laminar cracking process. The paper summarises progress in AMRL research which is investigating analytical and experimental approaches to laminar defect/fatigue interactions.

1 Corrosion management

Compared with the considerable research effort that currently being directed towards widespread fatigue damage in ageing aircraft, there has been relatively little research attention focussed on the shortcomings of conventional methods of structural integrity assessment in dealing with corrosion in primary aircraft structure. It is abundantly clear, however, that the uncertainties which corrosion introduces to structural integrity assessment can lead to substantial increases in maintenance and support costs and, in some instances, reduced aircraft availability. In extreme cases, these uncertainties could lead to imposition of unacceptable logistical burdens or aircraft retirement, thus threatening fleet viability.

In Australia, the RAAF have recognised that the importance of corrosion as a form of structural degradation is likely to increase as the age of several important RAAF fleets (including P-3C Orion, C-130 Hercules, F-111 and Boeing 707) approaches or even exceeds their original life of type. Historically, the approach adopted has been "find and fix". This leads to unacceptable costly maintenance burdens and major loss of availability while repairs are carried out. Unfortunately, the majority of these repairs are unwarranted in the sense that they probably do not represent any immediate threat to structural integrity, and they may even be completely unnecessary, presenting no threat during the life of the fleet. The problem is that any decision *not to repair* must be based on a sound understanding of any consequences – decisions affecting structural integrity must reflect the possible effects of in-service damage and degradation like corrosion even if this implies costly maintenance based on the need to take a conservative approach. How, then, can we know how severe any threat to safety might be?

As a result of a review of the impact of corrosion on aircraft structural integrity [1] AMRL proposed that the current "find and fix" approach be modified, by developing tools which will allow corrosion to be managed as part of an overall structural integrity management plan i.e. move to an "inspect and manage" philosophy. The key element in such a change is to be able to analyse corrosion using the well-developed approaches in use for cracking, and the AMRL research programs are

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2000	**N/A**	-

4. TITLE AND SUBTITLE	
The Significance Of Laminar Corrosion Defects In Aircraft	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **DSTO Aeronautical and Maritime Research Laboratory, Melbourne, Australia**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002333. International Congress of Aeronautical Sciences (ICAS) (22nd) Held in Harrogate, United Kingdom on August 27-September 1, 2000. U.S. Government or Federal Purpose Rights License, The original document contains color images.

14. ABSTRACT

Laminar corrosion defects, such as intergranular penetrations and stress corrosion cracks, are common in ageing aircraft. These defects are most commonly found in extruded and rolled sections made from high strength aluminium alloys; typical examples include wing and tailplane spar caps in widespread use in ageing aircraft. They present a significant problem in that the assessment of their significance is difficult, not only because their orientation (most commonly parallel to the direction of applied stress) makes analysis difficult using conventional stress analysis techniques, but because of the inherent variability of the laminar cracking process. The paper summarises progress in AMRL research which is investigating analytical and experimental approaches to laminar defect/fatigue interactions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

focussing on developing analytical techniques which will describe corrosion damage in terms of an Equivalent Initial Flaw Size i.e. an idealised fatigue crack which will give the same fatigue life as the corroded part. The research will define EIFS values for a range of corrosion types, with the aim of determining *which characteristics* of the corrosion define the EIFS. Knowledge of such characteristic features (corrosion "metrics") would then represent a useful tool for assessing specific cases of discovered corrosion. Currently, attention is being focussed on pitting and exfoliation corrosion in aluminium alloys and in high-strength steel.

2 Laminar corrosion defects

2.1 Background –SCC and exfoliation

Laminar corrosion defects make up a significant proportion of the corrosion discovered in aging aircraft fleets. The problem arises because the materials used in many aircraft still in service were selected on the basis of strength rather than corrosion resistance. Many, such as the widely used 7075-T6, suffer intergranular attack under the combined influence of stress and an aggressive environment such as moist air. Unfortunately, these materials often exhibit grain structures which provide an abundance of laminar paths inside the sheet or plate, making them particularly susceptible to corrosion penetrations along the plate-like grain boundaries, and hence to the possible occurrence of stress corrosion cracking wherever there is a stress acting through the plate thickness. Examples given later will demonstrate that the stress required may arise from structural features, or may be internal residual stresses or internal stresses.

Laminar defects such as those in SCC require access to the aggressive environment, and therefore tend to occur at exposed end-grain sites. Any surface discontinuity can expose such end-grain material, and exfoliation corrosion is a common occurrence at, say, fastener holes. Such corrosion presents itself as a progressive "peeling off" of material as grains are separated, since the development of corrosion product in the laminar fractures can provide a wedging action sufficient to cause further progression of the laminar defect.

2.2 Analysis of growth and failure of laminar defects

In terms of developing tools for analysing the effects of corrosion on structural integrity, laminar defects present a particularly challenging problem, for three reasons:

(a) Non-laminar cracking is usually associated with obvious stress-concentrators such as holes, and the most severe stress-concentration is usually the most likely initiation point for fatigue cracking. Accordingly, an analysis of the most severe stressing "hot-spot" will usually be sufficient to be sure that the most conservative approach is being taken for the component or assembly. . Laminar defects, however, while usually being associated with exposed end-grain, are often driven by internal stresses which are not obviously associated with physical features in the component, and can therefore occur at a wide variety of sites in a component. This uncertainty about potential defect locations greatly increases the number of sites to be considered, relative to the case of fatigue cracking, and prevents the use of well-established procedures for identifying potentially critical locations.

(b) Laminar defects are usually oriented along the direction of the maximum principal stress in the region. Hence, the failure condition needing to be addressed is unlikely to be simple tensile separation of a component – it may involve buckling instability of the component if the laminar defect is large, or bearing failure if there is extensive delamination at holes. Analyses therefore need to address a whole new set of failure conditions, outside the range normally considered in the design process.

(c) The continued growth of laminar defects is not usually predictable to any useful extent, being dependent on poorly-understood residual stresses and on uncertain environmental influences (which are themselves influenced by widely-varying factors such as environmental

access through coatings or joints). In situations where joints supply the driving stress, uncertainty about load transfer compounds the problem.

2.3 Laminar defects as fatigue initiators.

A possibility which always needs to be examined is that of the laminar defect initiating a fatigue crack which could then cause failure. Three situations exist, described here as Types I, II and III as illustrated in Fig.1.

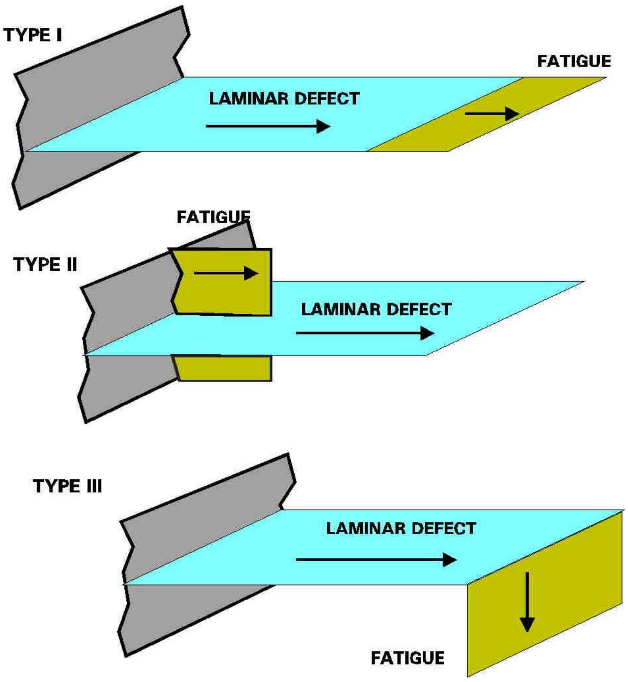

Figure 1. Three configurations in which fatigue cracking can be associated with laminar corrosion defects.

2.3.1 (Type I) In-plane growth

One mode (illustrated in Fig.2 below) involves the defect growing in-plane by fatigue. Normally, this would be unusual, since it would imply the presence of a significant fluctuating load across the plane of the crack.

Example: The component shown in Fig.2 is a high-strength steel splice plate. A corrosion pit formed at a point where the protective Cadmium plating had been damaged or removed; under the influence of a bending load on the component, the high stress at the tip of the flange led to stress-corrosion cracking. As this cracking progressed, however, it did so under a decreasing stress-intensity condition, and the growth rate slowed substantially as it reached the base of the flange. In this state, however, the fluctuating tensile loads on the component were acting on a fairly long crack, and the crack began to grow by fatigue.

This situation would be fairly rare, requiring a specific pair of stresses to be operating.

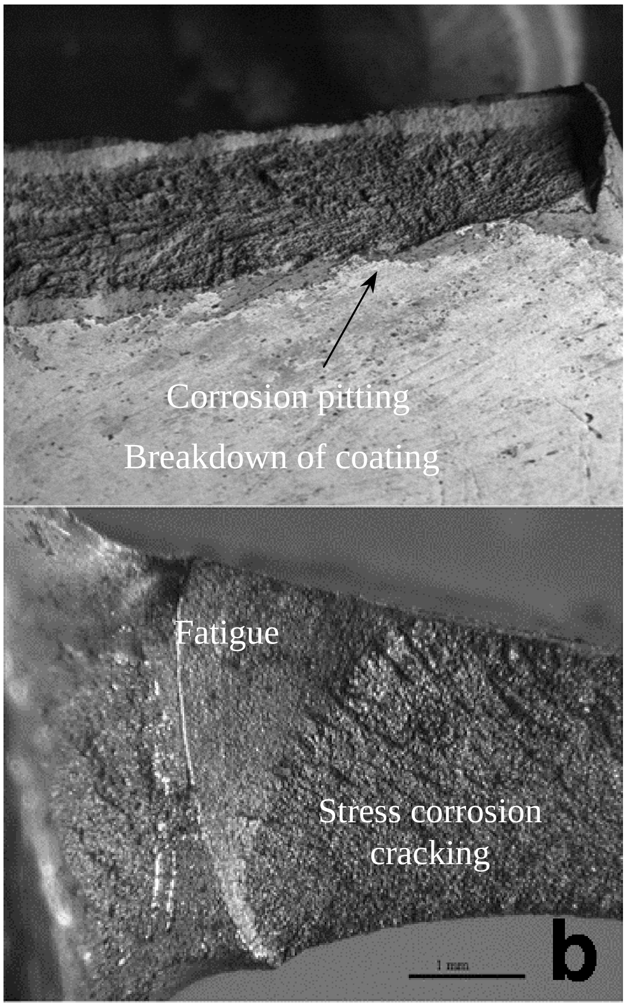

Figure 2. In-plane Stress Corrosion Cracking which then transitions to fatigue cracking. (a) The origin of the SCC at a pit, (b) the transition to fatigue.

2.3.2 (Type II) Fatigue crack normal to lamina (common growth direction).

The second mode (Type II) involves a situation where the fatigue crack and laminar defect intersect along a common growth direction.

<u>Example</u>:

In a component from a C130 aircraft, fatigue cracks were observed on the bores of holes. When these cracks were broken open for examination, Stress Corrosion Cracking (SCC) was observed in an unusual configuration (Fig 3); an array of SCC cracks had developed growing, as is normal for SCC, perpendicular to the through-thickness direction for the part. The array therefore intersected the fatigue crack, and was observed to be interacting with it. The fatigue crack and the SCC were extending in the same direction. Firstly, the fatigue crack front was made up of separate curved fronts between the SCC cracks, consistent with the SCC acting as a free surface. Secondly, the SCC appeared to be growing ahead of the fatigue by a consistent amount, suggesting that its advance was linked in some way to that of the fatigue crack. Such a situation could occur if the fatigue crack was controlling the supply of fresh environment to the SCC crack tip, or if the presence of the fatigue crack was reducing the stresses which were driving the SCC.

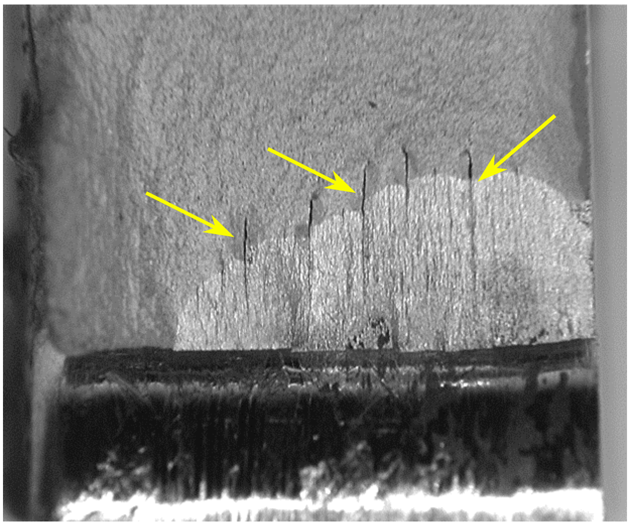

Figure 3. Complex interaction between SCC and fatigue cracking.

2.3.3 (Type III) Fatigue crack normal to lamina (growth normal to lamina)

The third, and most worrying configuration is one where a laminar defect generates a fatigue crack which then grows under the influence of the local principal stress i.e. the laminar defect acts as an initiator for a "conventional" fatigue crack orientation.

<u>Example:</u>

During inspection of RAAF Macchi MB326H aircraft, laminar stress corrosion defects were discovered in tailplane spars. The defects (Fig 4) had a variety of configurations, including following cylindrical surface. Etching of a section revealed that cracking followed the grain flow of the extruded material, suggesting poor properties across the grains, as well as a residual stress distribution which includes radial tensile sustained stress. The surfaces of the cracking revealed complex progression marks, although it is not yet possible to related these to fluctuations in stress or environment.

The question of airworthiness had to be answered, and it was clear that it was not possible to guarantee that fatigue cracks would not develop over the course of the next five years or so. This meant that the spars had to be replaced, but this raised yet another question – could the spars remain in service until replacements were manufactured. In the event, it was possible to maintain a small but effective fleet after a detailed review of the situation, and introduction of a number of remedial measures. One of these measures was the use of water-displacing corrosion preventatives (WDCPs) which have been also been used on large laminar stress corrosion defects in C130 aircraft. In that application, the use of the WDCPs has been effective in retarding further development of the SCC cracking.

The Macchi SCC cracking was a serious threat to the continued operation of the RAAF fleet, and it was our lack of knowledge about the likelihood of fatigue crack growth from laminar defects which was a significant factor. The incident focussed increased attention on the behaviour of laminar defects.

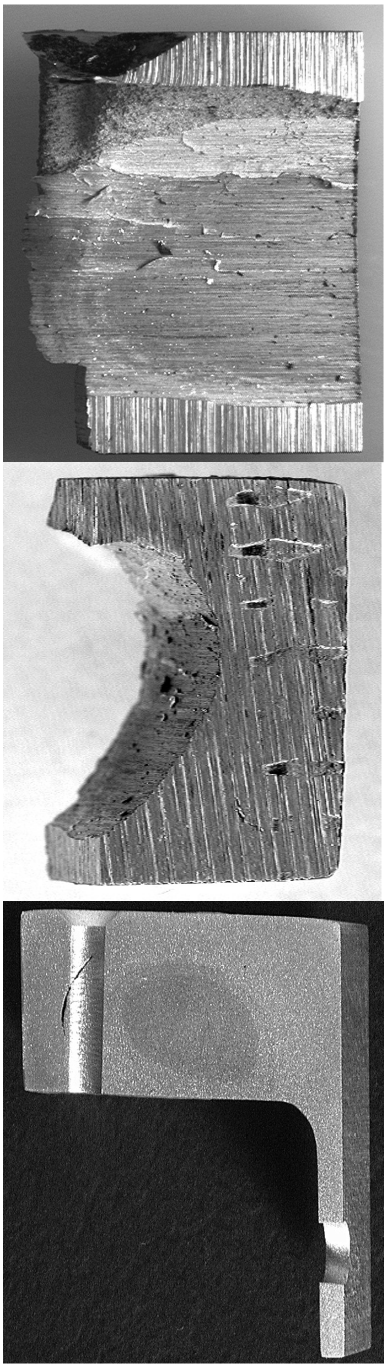

Figure 4. SCC in tailplane spar
(a) SCC crack surface, showing progression markings
(b) second example,
(c) section showing cylindrical configuration of SCC and association between microstructure and cracking.

2.3.4 Simple analysis of lamina/fatigue.

The problem with attempting to assess the likelihood of a fatigue crack developing at the tip of a laminar defect and growing normal to the principal stress this situation is that the alignment of the lamina with the principal stress prevents analysis of growth of fatigue cracks from the tip on the basis of symmetry; i.e. which way would the crack grow – both directions are equally likely. To begin to address this, a simple analysis was used. This was based on the assumption of a damage-tolerant approach i.e. the existence of a standard small fatigue defect was assumed for various locations within a component, and the severity of that defect was assessed using standard solutions for the stress intensity factor. In effect we postulate that a fatigue crack will grow when the laminar defect of length *L* encounters an initial fatigue defect of length *2a* oriented favourably for fatigue i.e. normal to the applied stress, and normal to the laminar defect.

Figure 5 shows the component situation; a small defect (depth *2a*) is considered at three locations:

(A) a crack at the tip of a laminar defect, length *L*, and extending to one side of the lamina.)

(B) at the surface of the part (edge crack)

(C) internal defect remote from the surface (buried defect)

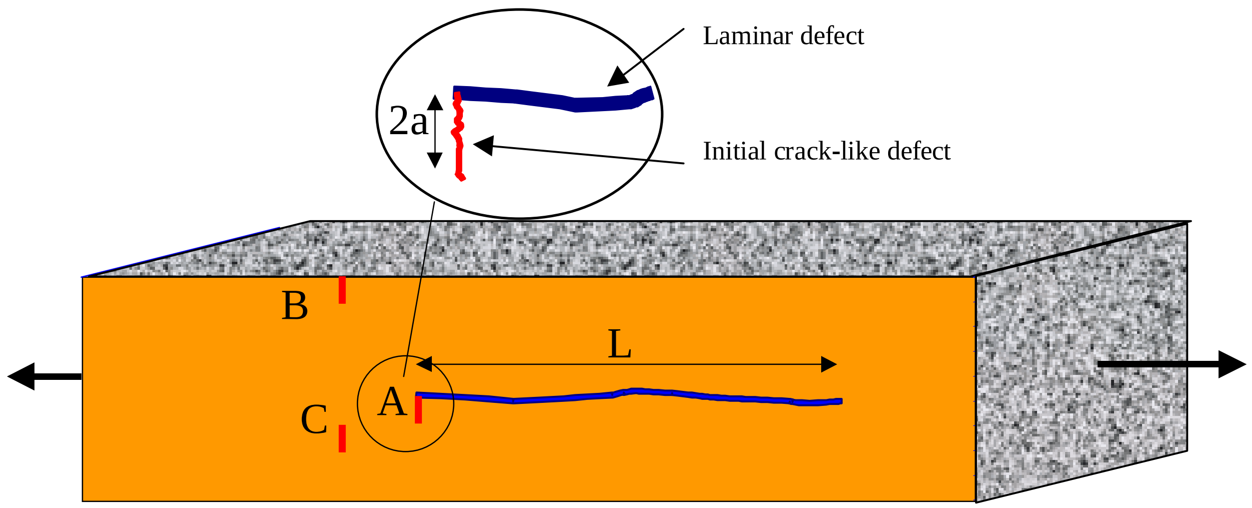

Figure 5. Idealised geometry of component containing three configurations of initial fatigue crack.

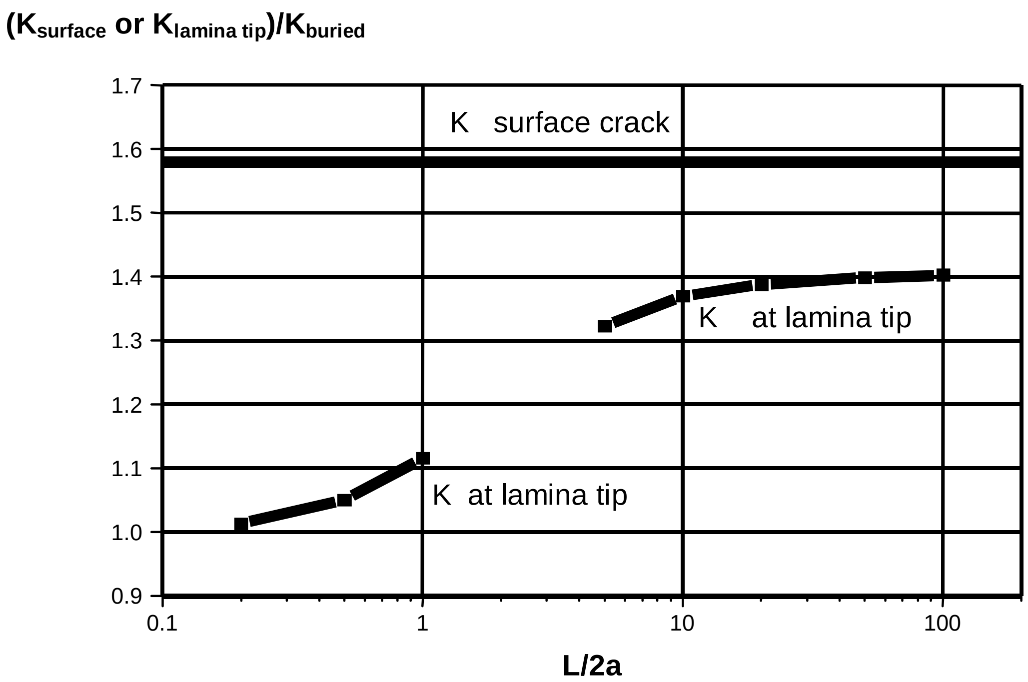

Figure 6. Stress intensity factor solutions, normalised by the "buried crack" result.

Stress-intensity solutions for the three configurations are shown in Figure 6, for a range of laminar defect sizes (i.e. L/2a ratio).

To identify the effect of the laminar defect on the propensity of the initial defect to propagate (situation A above), we compare the Mode I stress intensity factor at the free tip (t) of the initial defect with that at the same defect buried in the material C or at the free surface B.

Making use of stress intensity factor solutions by Chatterjee [2] and by Isida and Nishino[3] we can obtain the ratio K_A/K_C as shown in Fig. 6. Clearly, for any L/2a > 10 the defect at the laminar flaw tip has a stress intensity about 1.4 times that for the free internal defect, while the equivalent ratio (K_B/K_C) for the surface-breaking initial defect is 1.58. The result is very insensitive to L/2a. In other words, the laminar

defect makes the internal defect more likely to propagate as a fatigue crack, but has less effect than the defect being at a free surface. The length of the laminar defect does not appear to be important.

This simple analysis lends some support to the suggestion that fatigue from the tip of a laminar defect is not something to be particularly concerned about, although obviously each specific geometry should be considered in detail, and the presence of an aggressive environment could alter this situation. The approach taken, however, is important, in that it could be used to assess individual geometries and situations where there is a need to assess airworthiness. Further analysis will deal with the possibility that a fatigue crack could be generated at a microscopic feature on the laminar defect.

2.3.5 Full scale testing.

A current program at AMRL is addressing the question of assessing the likelihood of a fatigue crack developing at the tip of a laminar defect by testing full scale structural components which are believed to contain laminar SCC defects. The program is at an early stage, but as yet, all fatigue cracks have been generated at the expected high stress locations in the structure. SCC cracking in neighbouring areas shows no evidence of substantial fatigue crack growth, perhaps reinforcing the conclusion reached in the last section. Further examination of the fracture and SCC regions is however necessary. A related program is examining aircraft spars containing known SCC, to determine whether the SCC influences the growth of fatigue cracking. Results to date suggest that there is minimal interaction.

The presence of laminar defects in aging aircraft needs to be considered in order to ensure that airworthiness is not compromised. There are several difficulties associated with environmental and geometric factors, some of which are being addressed by current research. One simple analysis proposed suggests that the possible growth of fatigue cracking from the tip of a laminar defect is not likely, and could represent a means of assessing individual cases to provide some indication of airworthiness.

3. Conclusion

The presence of laminar defects in aging aircraft needs to be considered in order to ensure that airworthiness is not compromised. There are several difficulties associated with environmental and geometric factors, some of which are being addressed by current research. One simple analysis proposed suggests that the possible growth of fatigue cracking from the tip of a laminar defect is not likely, and could represent a means of assessing individual cases to provide some indication of airworthiness.

4 References

[1] "The Implications of Corrosion with respect to Structural Integrity" Cole, G.K., Clark, G. and Sharp, P.K., Research Report, DSTO-RR-0102, Defence Science and Technology Organisation, April 1997.

[2] "The Stress Field in the Neighbourhood of a Branched Crack in an Infinite Elastic Sheet", Chatterjee, S., Int .J Solids Structures, 11, 521-538 (1975).

[3] "Formulae of Stress Intensity Factors for Bent Cracks in Plane Problems", Isida, M. and Nishino, T., Trans .Japan Soc .Mech. Engrs., 48-430, 729-738 (1982).